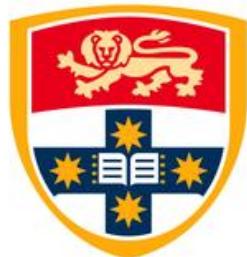


Planck constraints on neutrino physics

Jan Hamann



ICHEP 2016, Chicago
5th August 2016



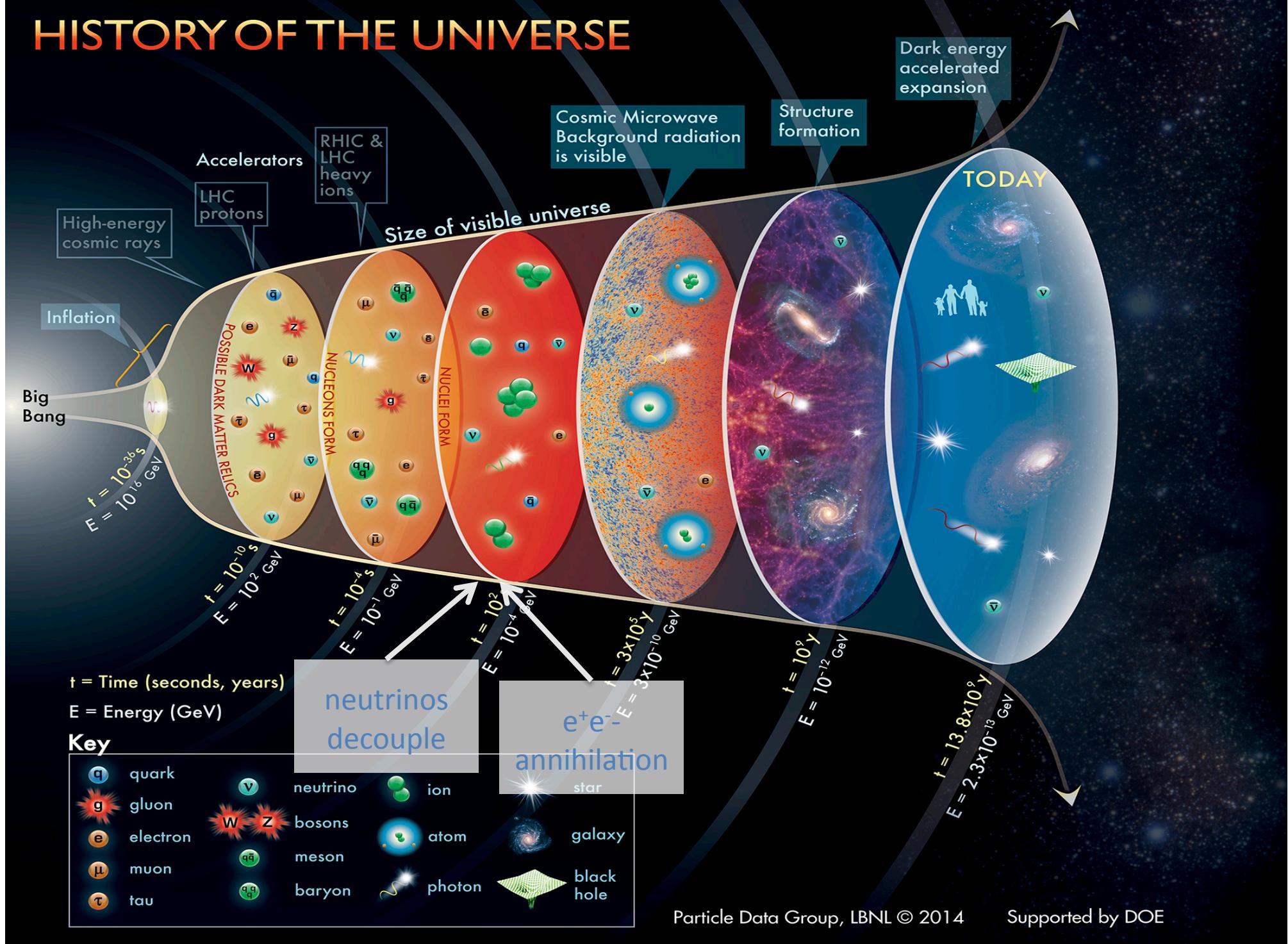
THE UNIVERSITY OF
SYDNEY



Australian Government
Australian Research Council

Neutrinos in cosmology

HISTORY OF THE UNIVERSE



The Cosmic Neutrino Background (CvB)

- Neutrino decoupling around $T = 1$ MeV, shortly before $e^+ + e^- \rightleftharpoons \gamma + \gamma$ goes out of equilibrium
- Annihilation heats CMB relative to CvB

$$T_{\text{C}\nu\text{B}} \approx T_{\text{CMB}}(4/11)^{1/3} \approx 1.95 \text{ K}$$

- Neutrino mixing equilibrates momentum distributions
- If $T_{\text{reheating}} > 10$ MeV, all three flavours populated

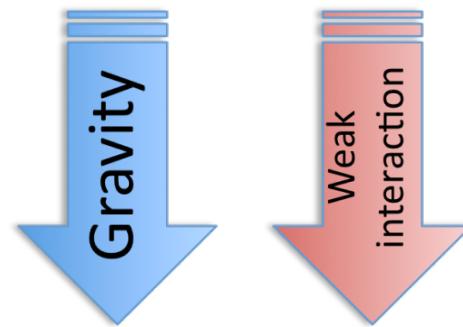
$$\bar{n}_\nu \approx 6 \times 56 \text{ cm}^{-3}$$

Impact of cosmological neutrinos

Structure formation



Neutrinos



Big Bang Nucleosynthesis

Neutrino parameters

How much energy density do neutrinos contribute...

... at early times?

$$\rho_r = \rho_\gamma \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \right]$$

Diagram illustrating the components of the radiation energy density ratio:

- Photon energy density (blue arrow pointing to ρ_γ)
- Fermi-Dirac vs. Bose-Einstein (blue arrow pointing to the coefficient $\frac{7}{8}$)
- Lower neutrino temperature (blue arrow pointing to the factor $\left(\frac{4}{11} \right)^{4/3}$)
- Radiation energy density (blue arrow pointing to ρ_r)
- Effective number of neutrino species (red arrow pointing to N_{eff})

$$\Lambda\text{CDM: } N_{\text{eff}} = 3.046$$

(small deviation from
Fermi-Dirac)

Neutrino parameters

How much energy density do neutrinos contribute...

... at early times?

$$\rho_r = \rho_\gamma \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \right]$$

photon energy density

Fermi-Dirac vs. Bose-Einstein

lower neutrino temperature

radiation energy density

Effective number of neutrino species

... at late times?

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93 \text{ eV}}$$

neutrino energy density

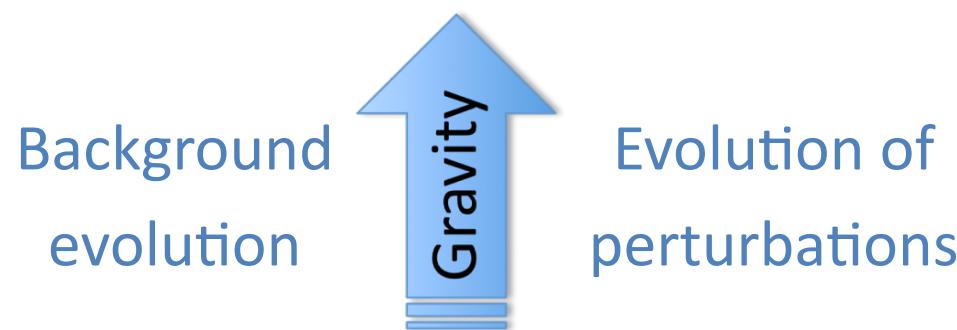
Sum of neutrino masses

Λ CDM: $N_{\text{eff}} = 3.046$
(small deviation from Fermi-Dirac)

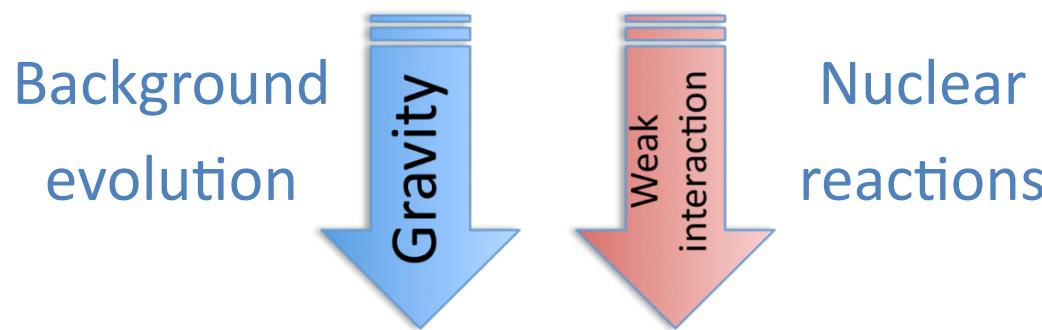
Λ CDM: $\sum m_\nu = 0.06 \text{ eV}$
(assumes lightest mass state is massless)

Impact of cosmological neutrinos

Structure formation



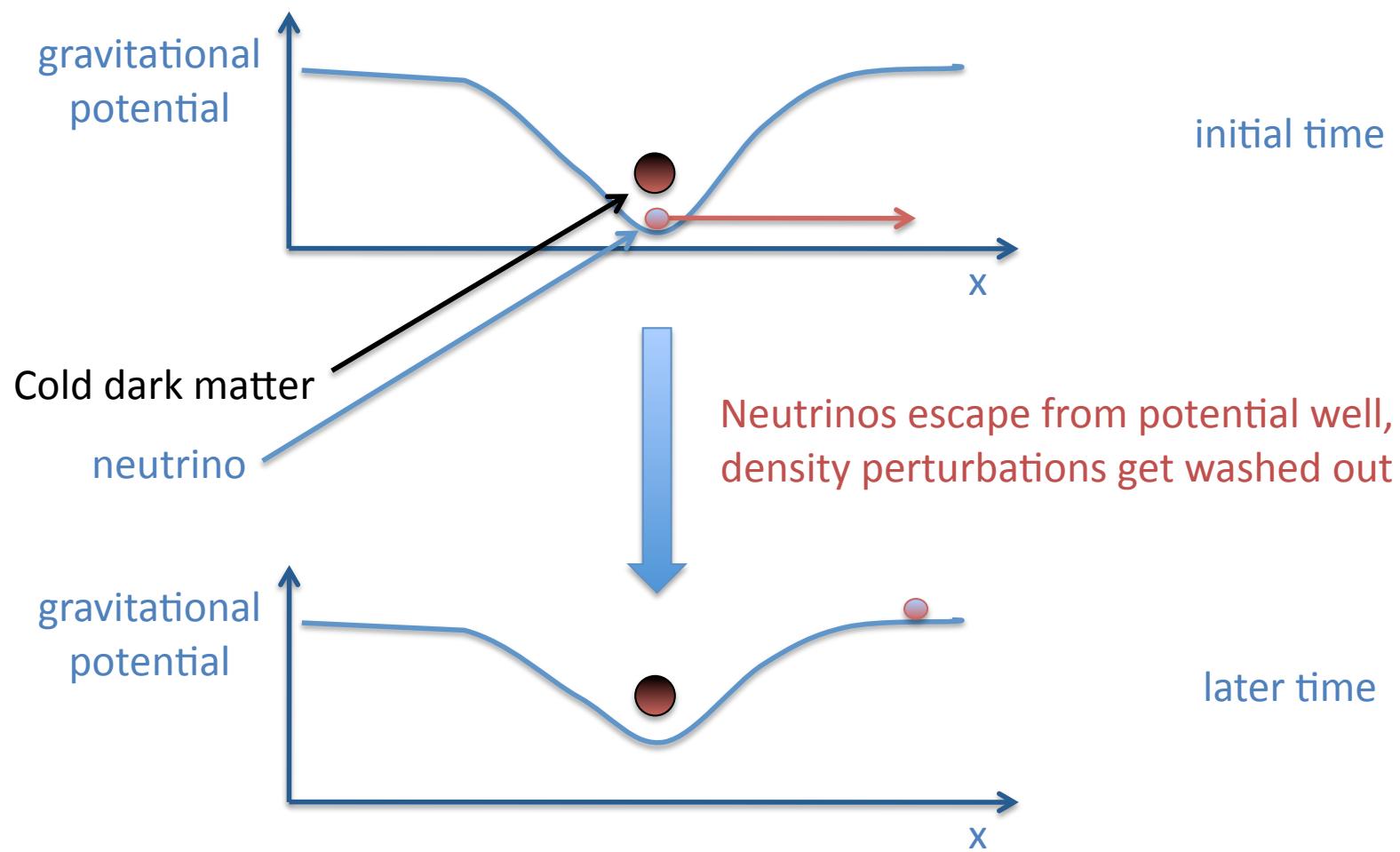
Neutrinos



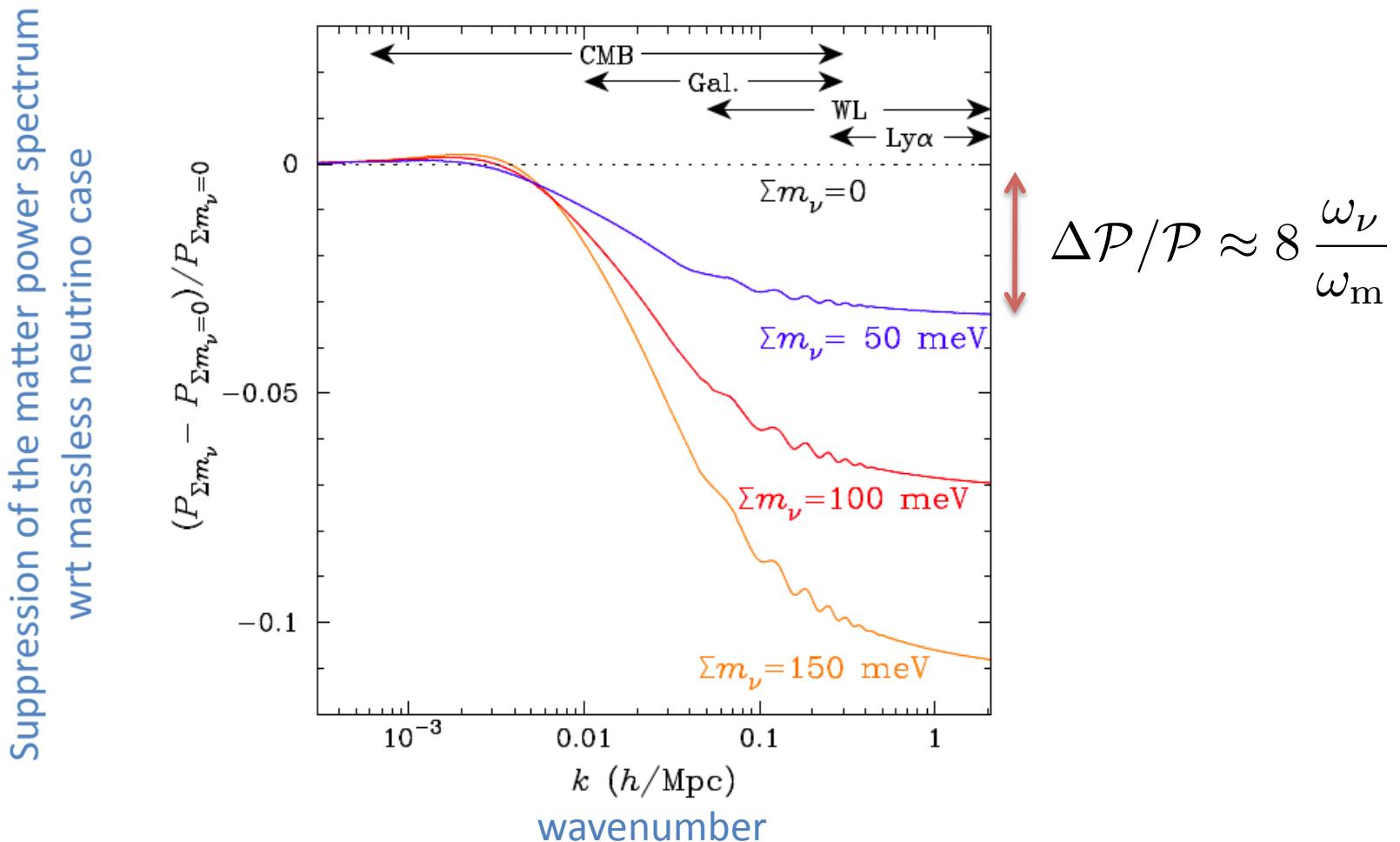
Big Bang Nucleosynthesis

Free streaming

Velocity dispersion large wrt size of potential well



Matter power spectrum with massive neutrinos (at low redshifts)



[Figure from Abazajian+ 2013]

Planck constraints on neutrinos



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and Analysis Center



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planck



The *Planck* mission (2009-2013)

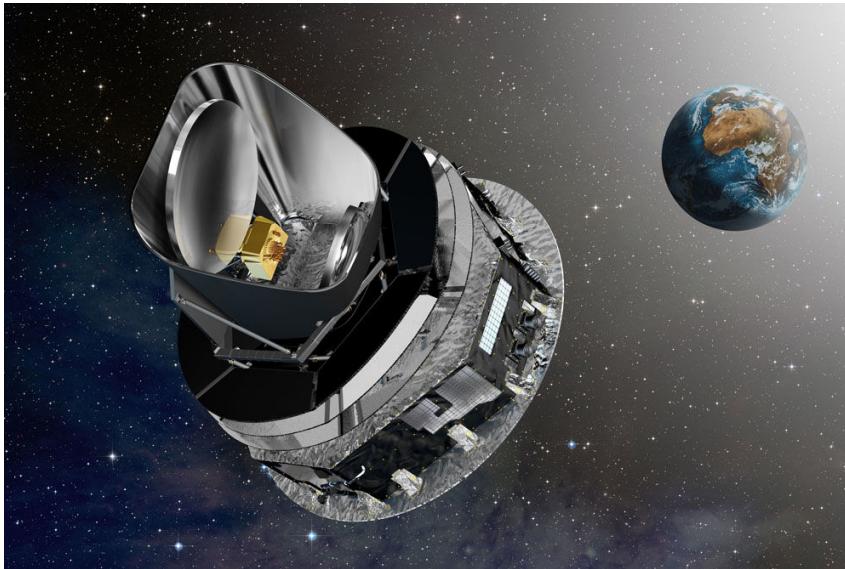
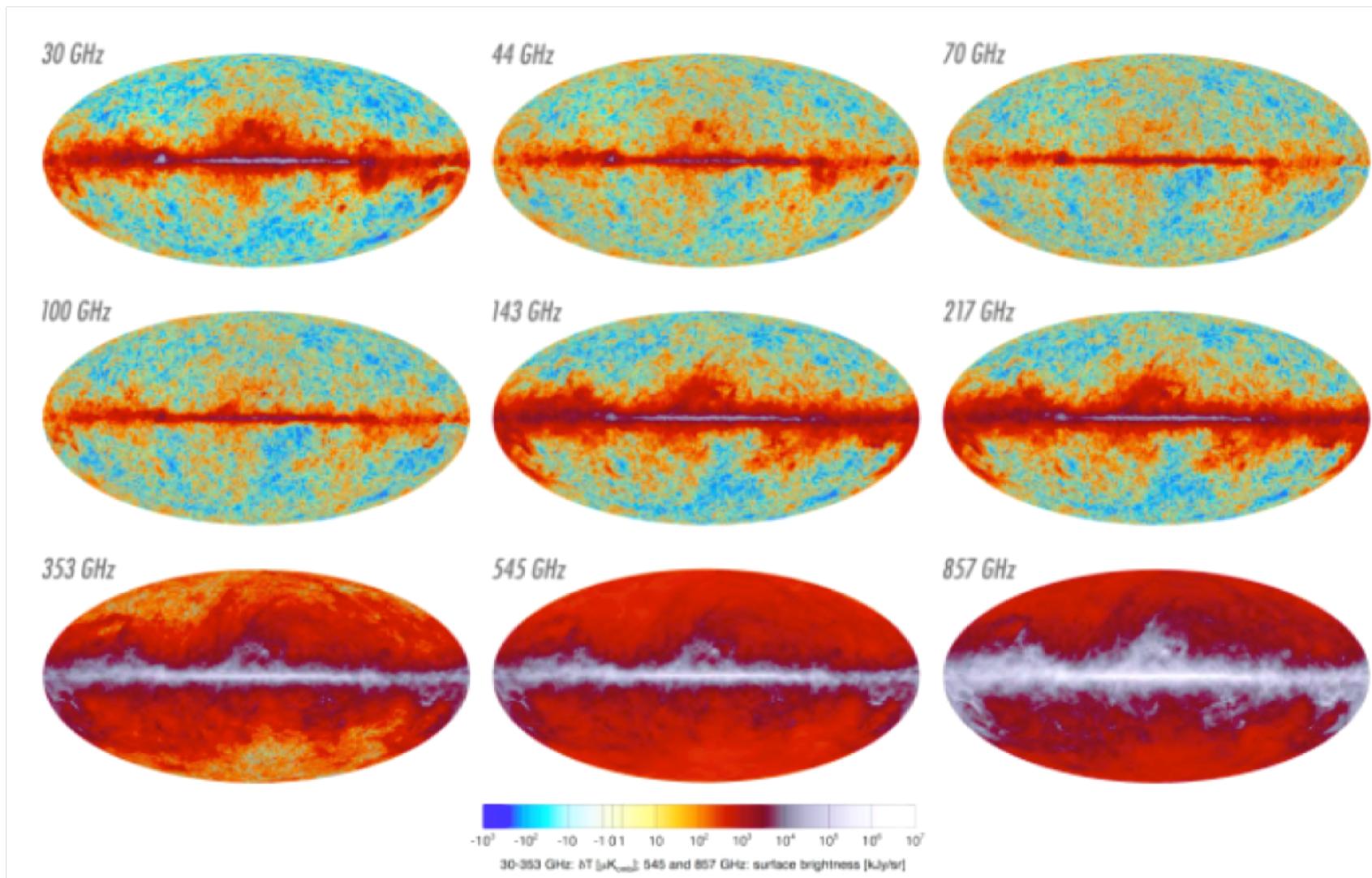


Table 2. *Planck* performance parameters determined from flight data.

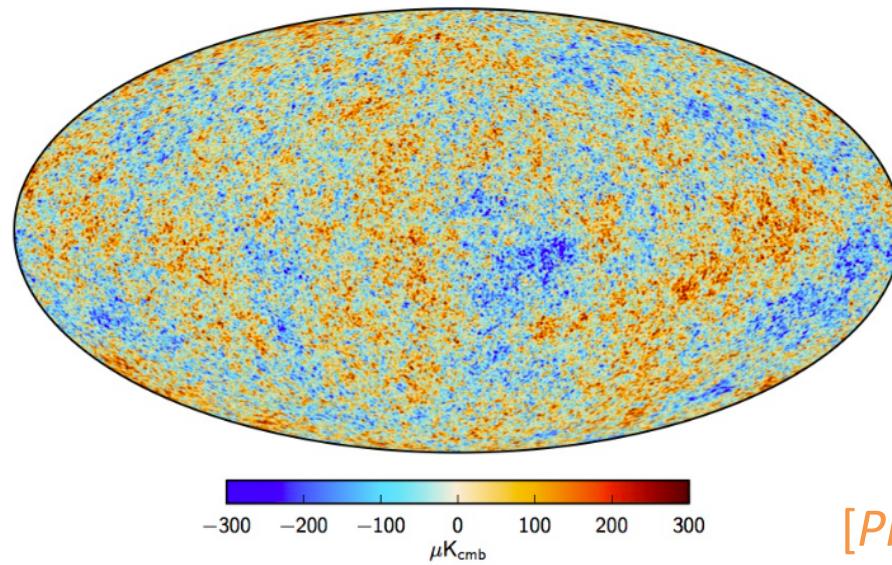
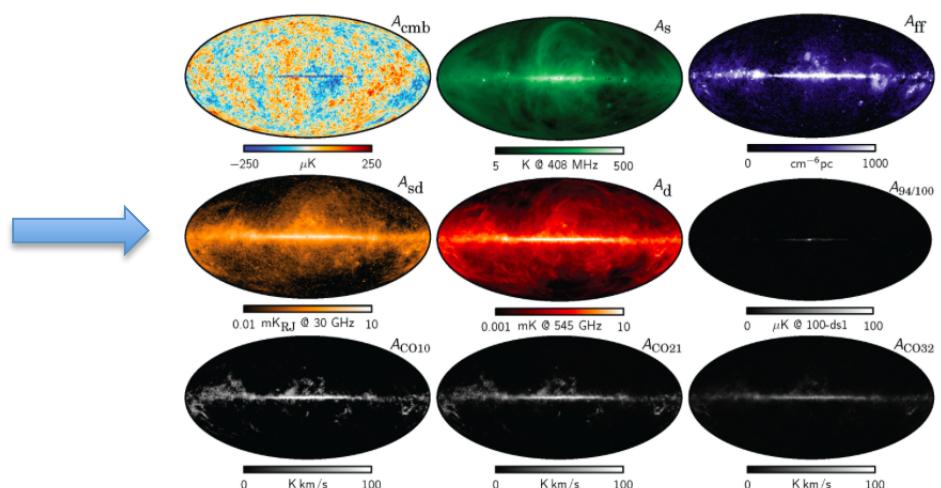
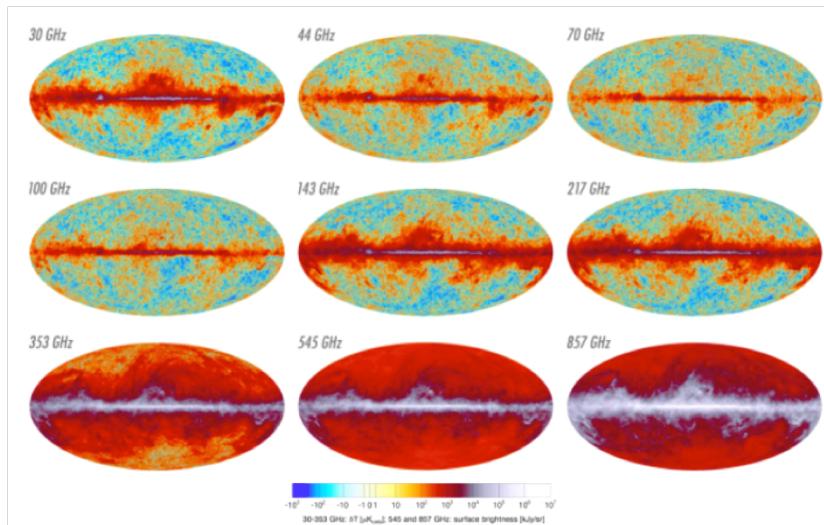
CHANNEL	$N_{\text{detectors}}^{\text{a}}$	$\nu_{\text{center}}^{\text{b}}$ [GHz]	SCANNING BEAM ^c		NOISE ^d SENSITIVITY	
			FWHM [arcmin]	Ellipticity	$[\mu\text{K}_{\text{RJ}} \text{s}^{1/2}]$	$[\mu\text{K}_{\text{CMB}} \text{s}^{1/2}]$
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.0259 ^d
857 GHz	4	857	4.51	1.38	1.33	0.0259 ^d

Planck sky maps



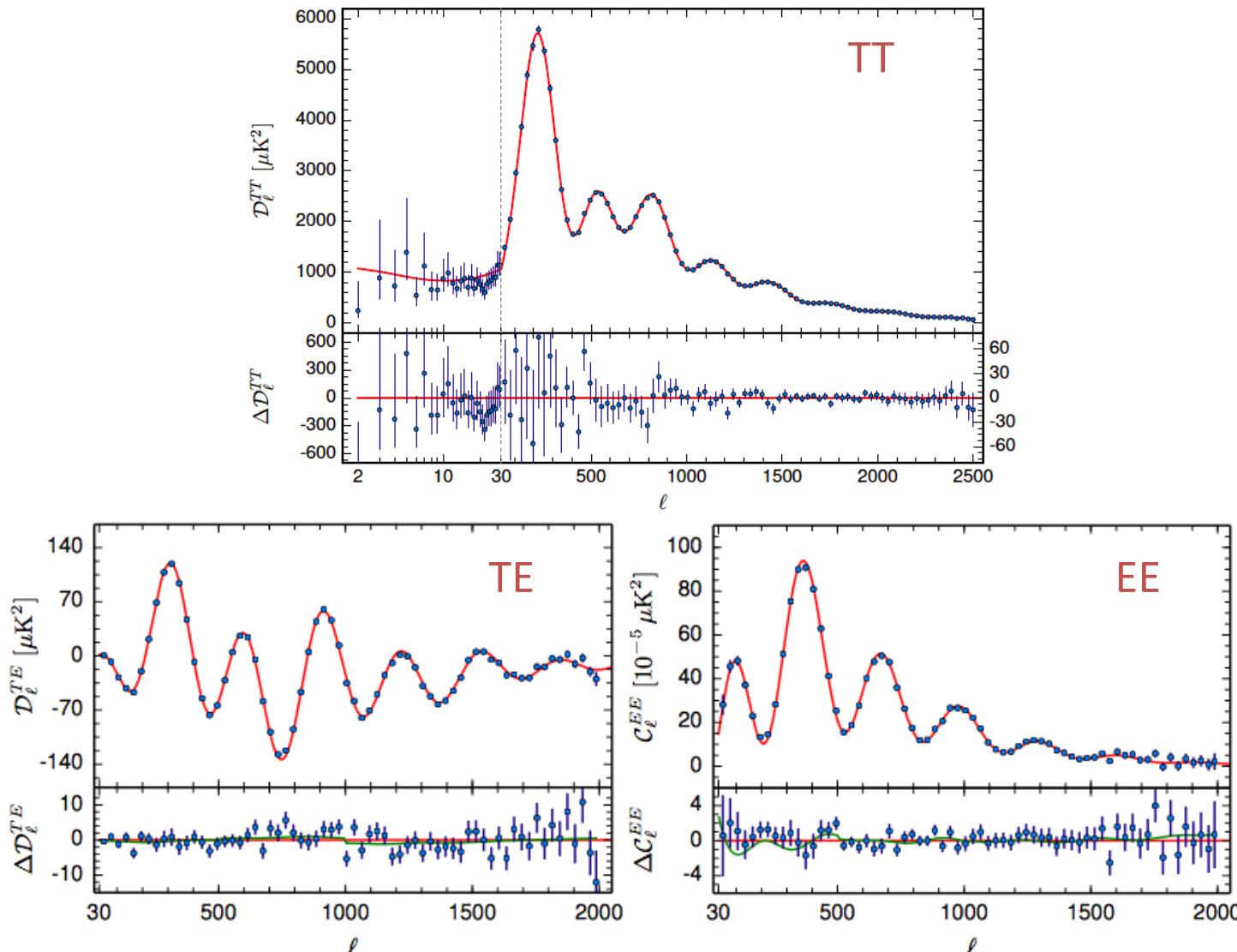
[Planck collaboration 2015]

Component separation and CMB map



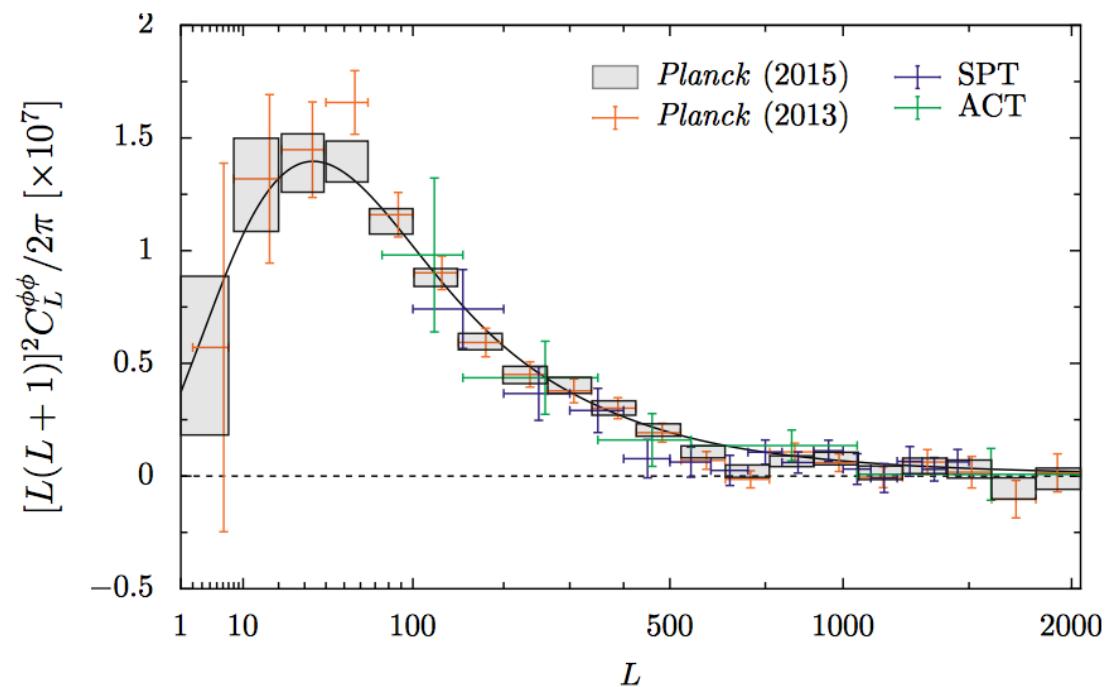
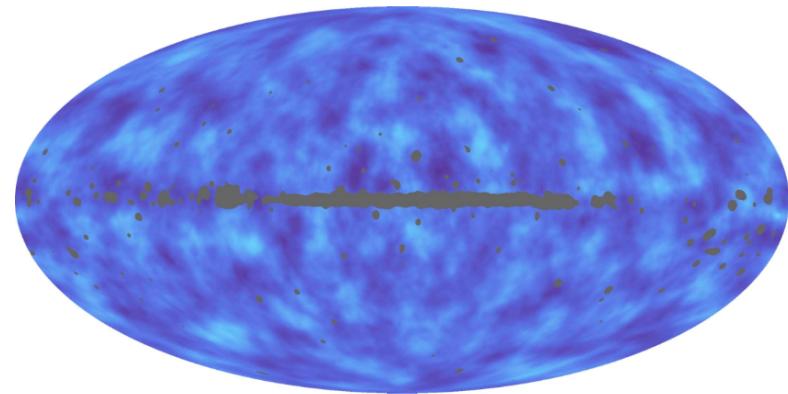
[Planck collaboration 2015]

CMB angular power spectra

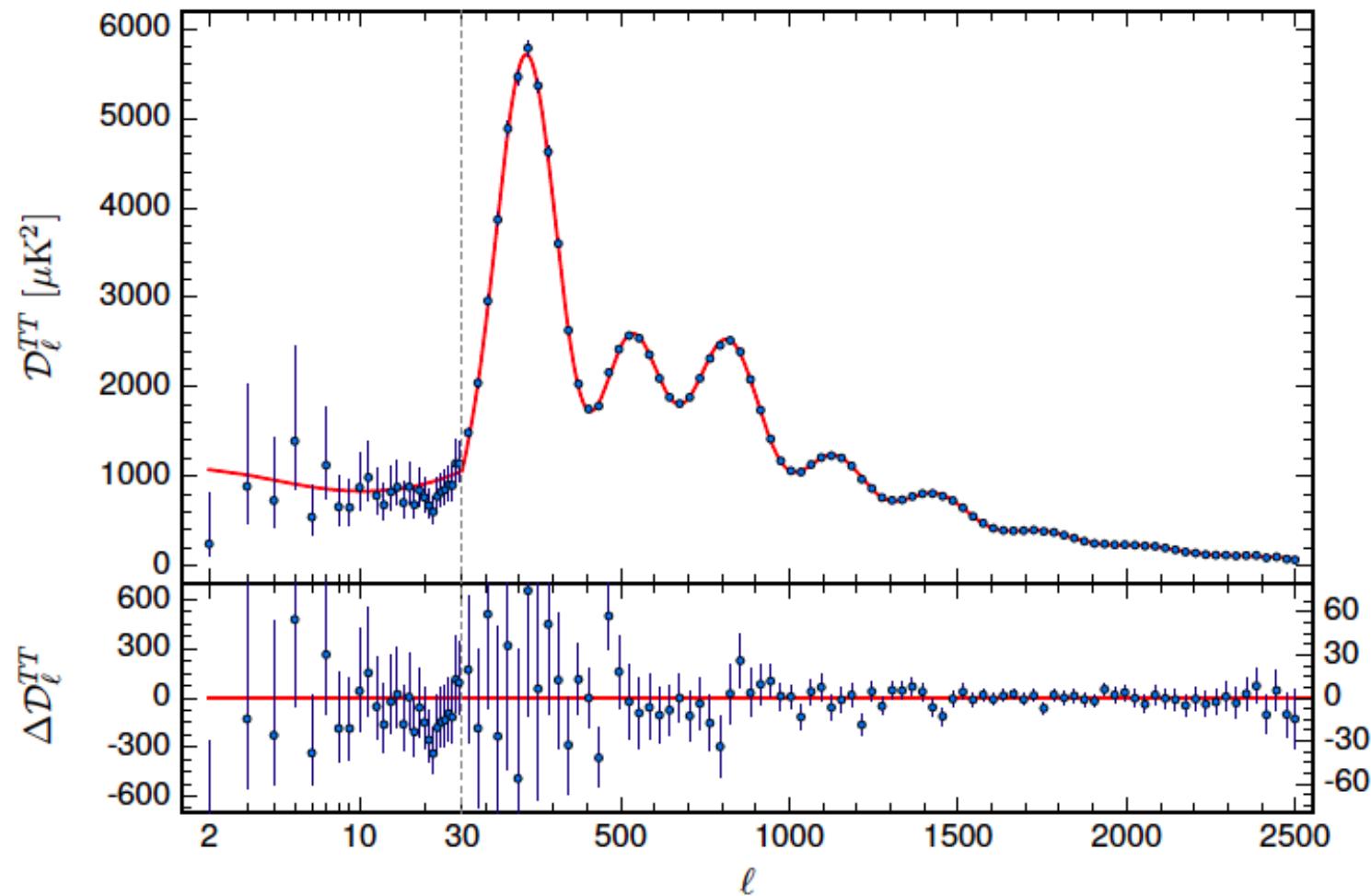


[Planck collaboration 2015]

CMB lensing potential

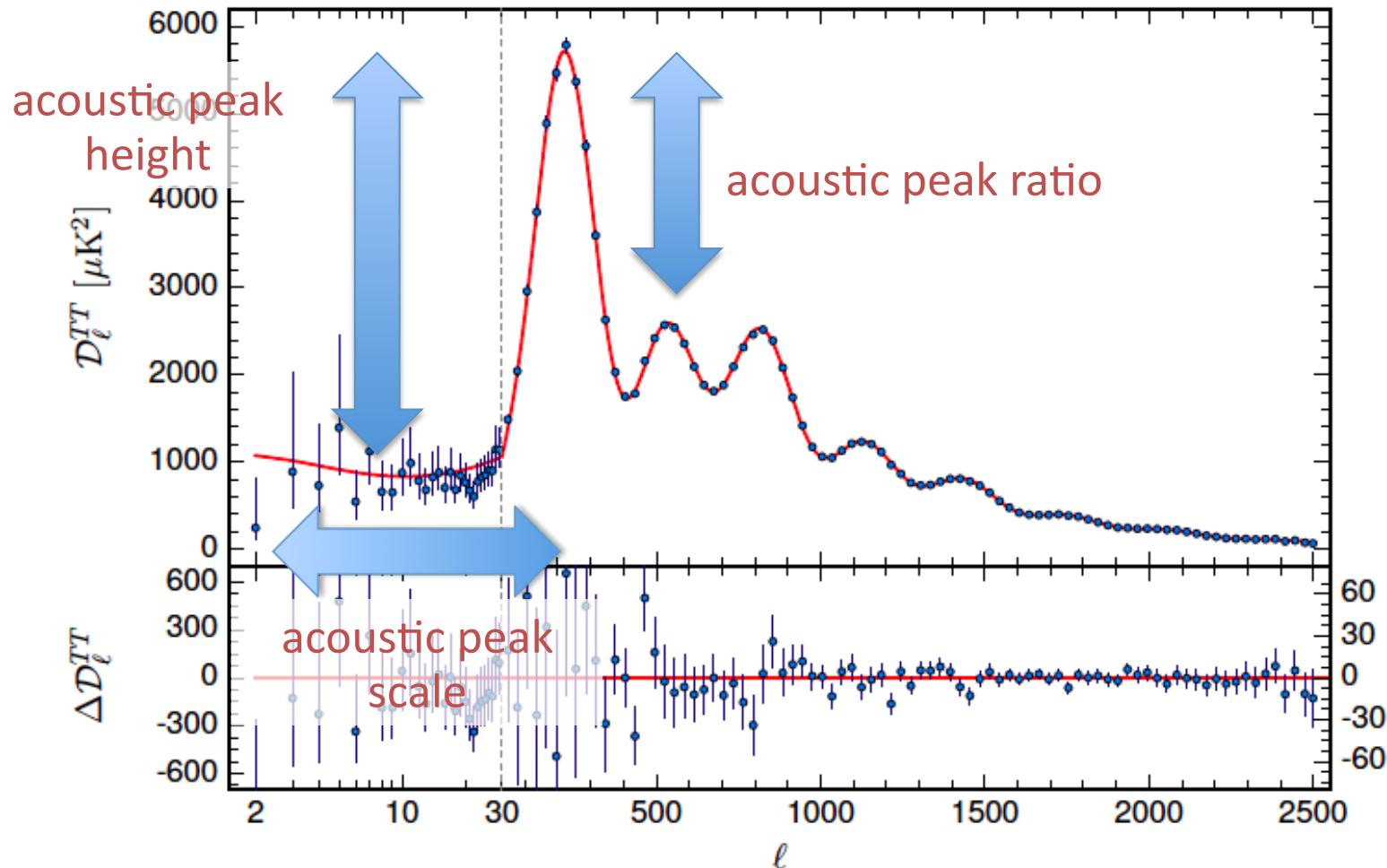


CMB TT angular power spectrum



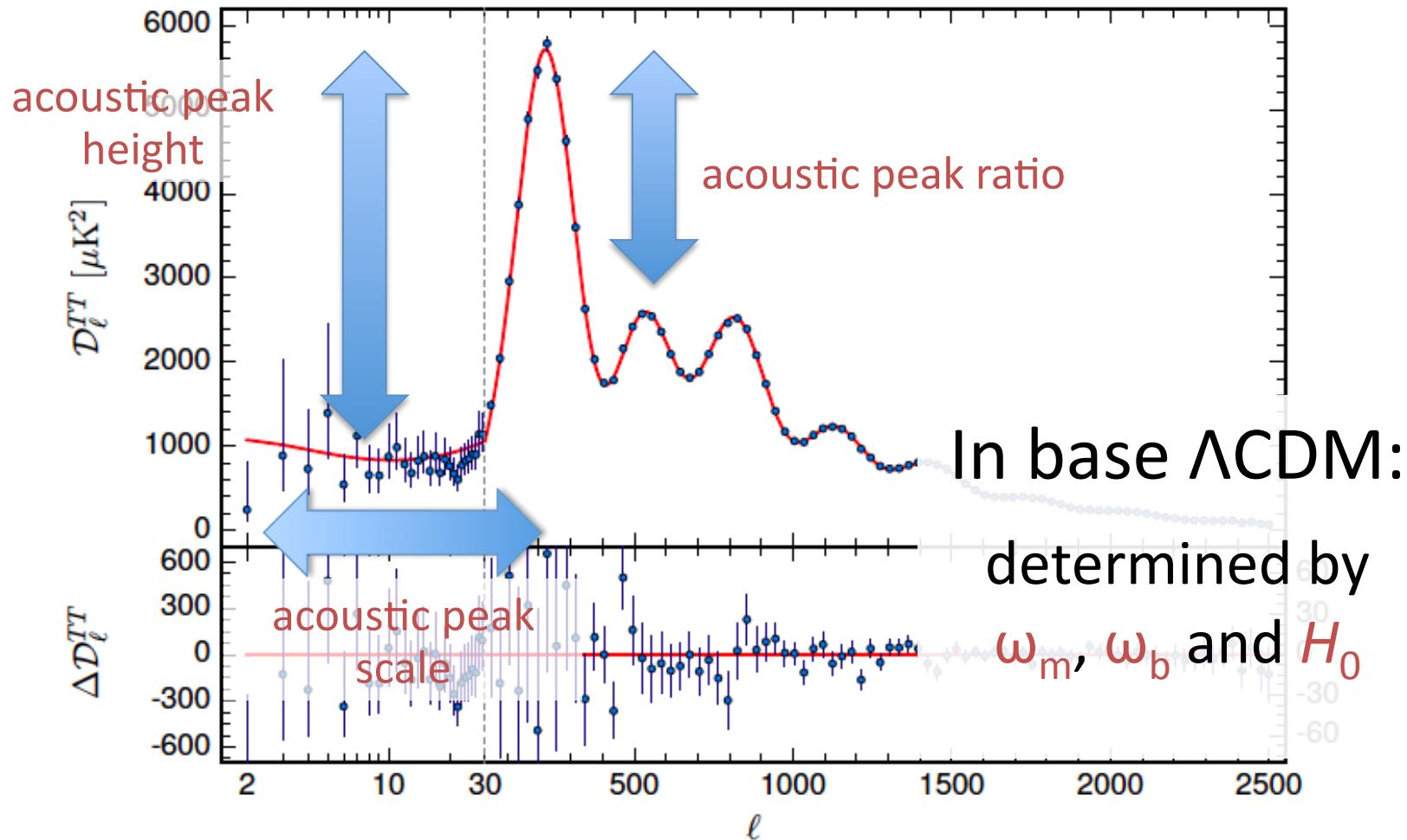
[Planck collaboration 2015]

CMB TT angular power spectrum



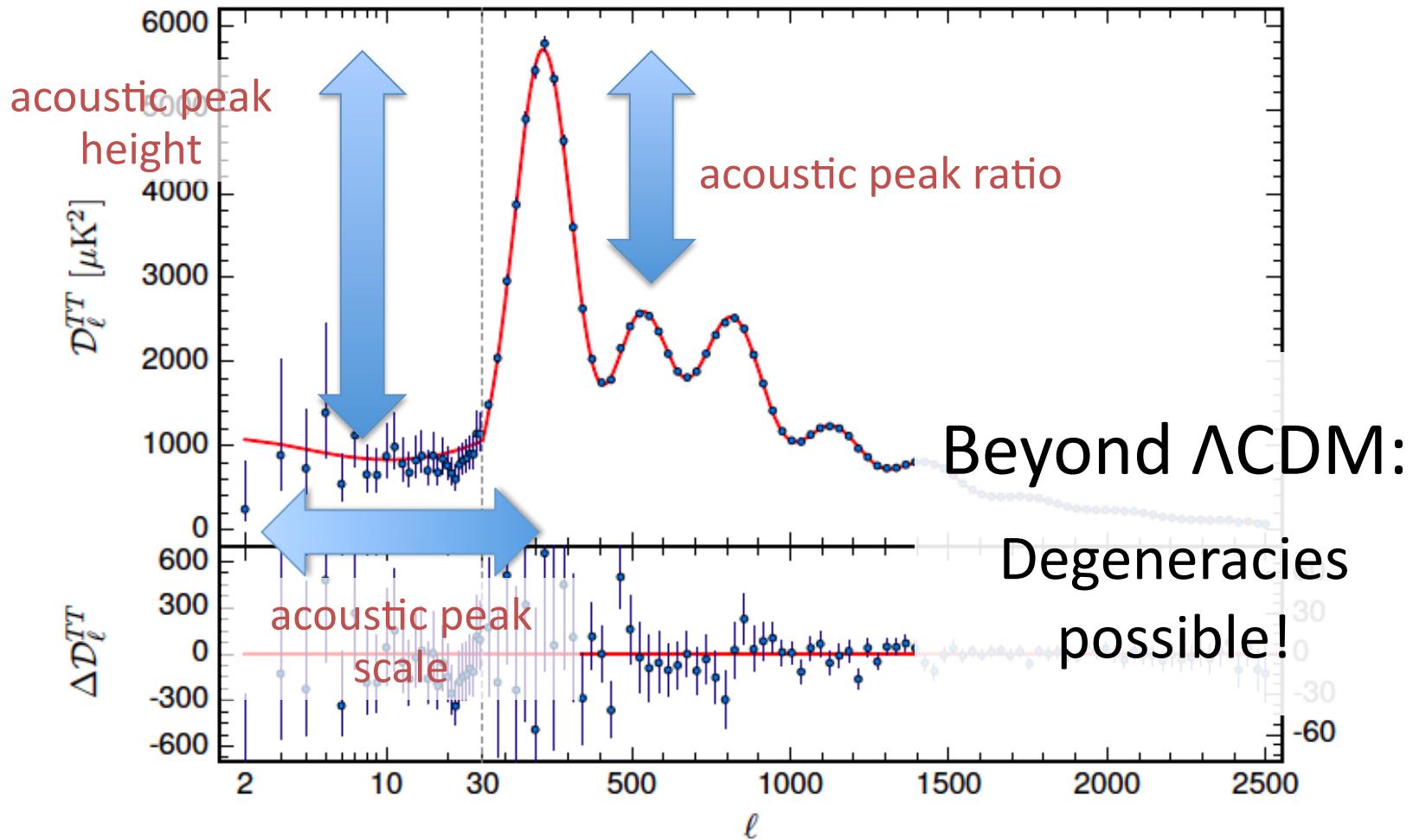
[Planck collaboration 2015]

CMB TT angular power spectrum



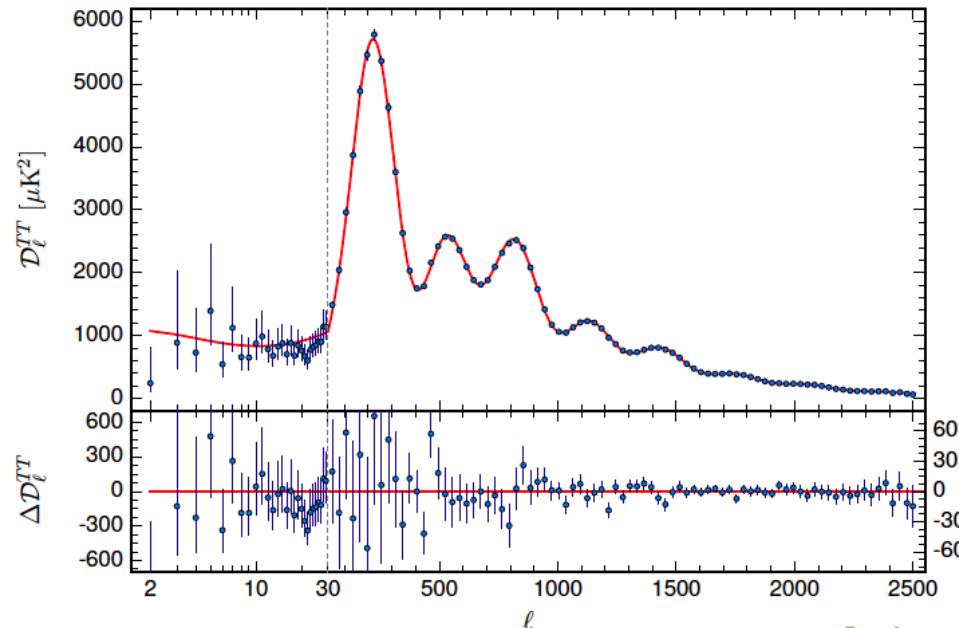
[Planck collaboration 2015]

CMB TT angular power spectrum



[Planck collaboration 2015]

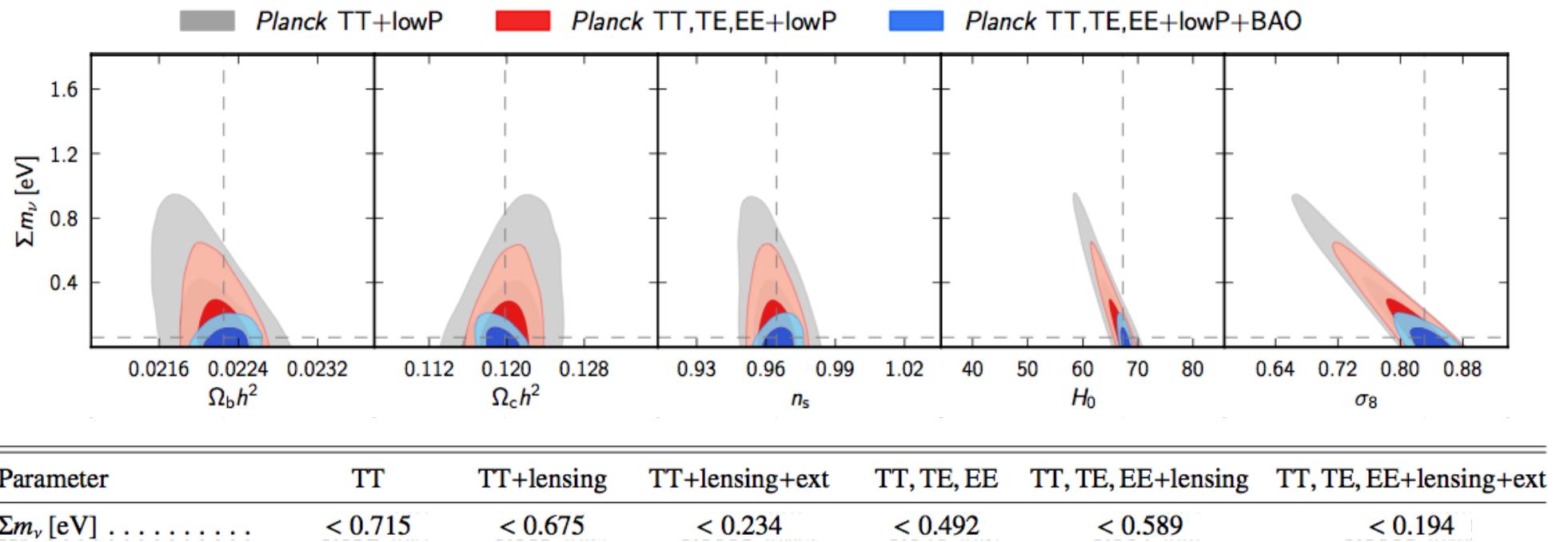
Neutrino masses and the CMB angular power spectrum



[Planck collaboration 2015]

- Changing neutrino mass affects z_{eq} and $d_A(z_{\text{rec}})$
- Can shift CMB peaks back in place by tweaking ω_c and H_0
(geometric degeneracy of the CMB)
- Remaining effects (early ISW, late ISW, lensing) rather subtle for sub-eV masses

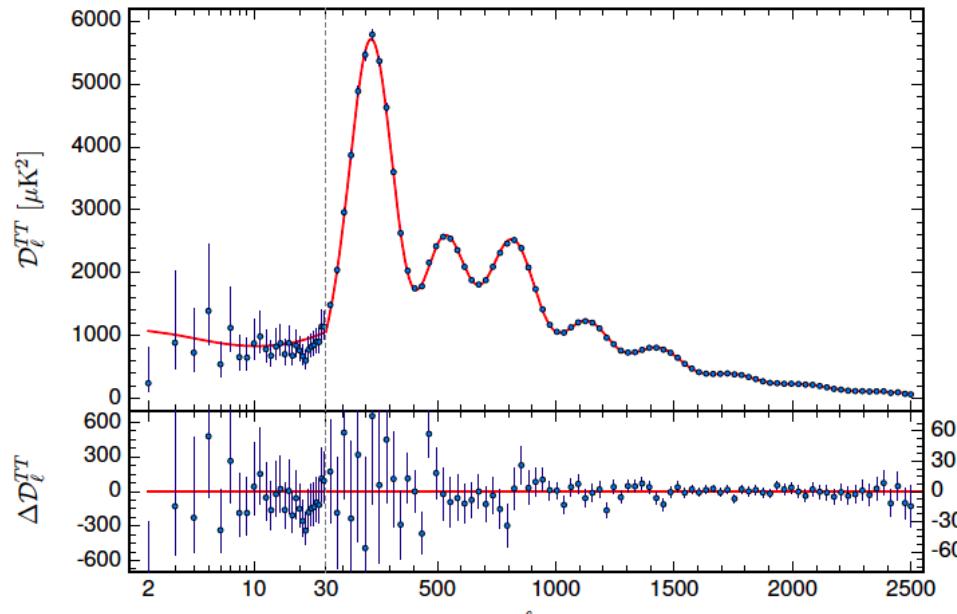
Planck constraints on the sum of neutrino masses



No sign of non-zero neutrino masses...

[*Planck* collaboration 2015]

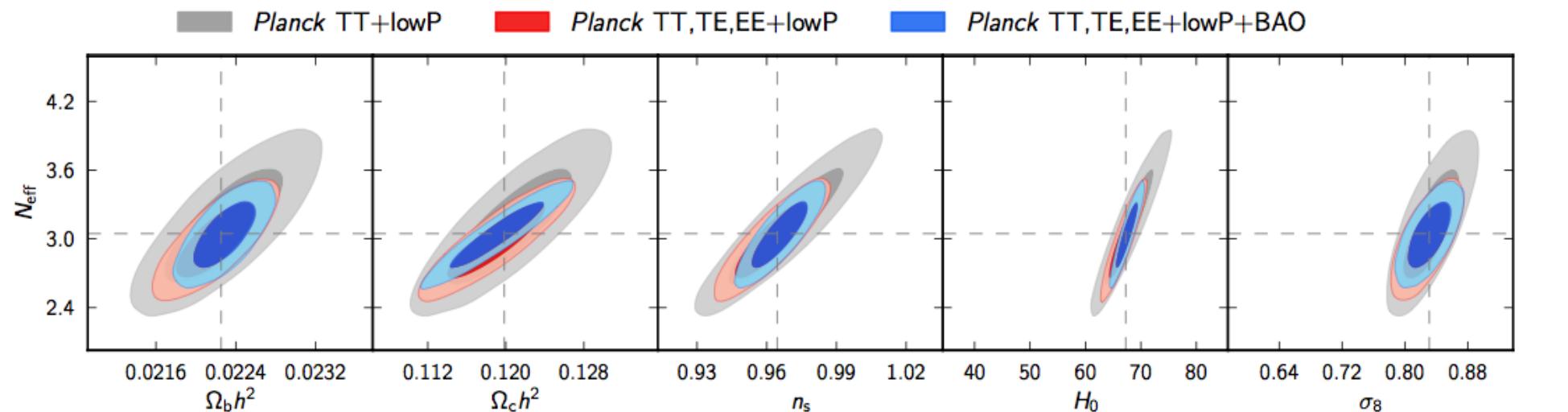
Effective number of neutrinos and the CMB angular power spectrum



[*Planck* collaboration 2015]

- Also subject to geometric degeneracy
- In addition, changes damping scale, anisotropic stress (partially degenerate with spectral index/amplitude of primordial spectrum)
- *Planck* measurement of damping tail greatly improved sensitivity

Planck constraints on the effective number of relativistic species

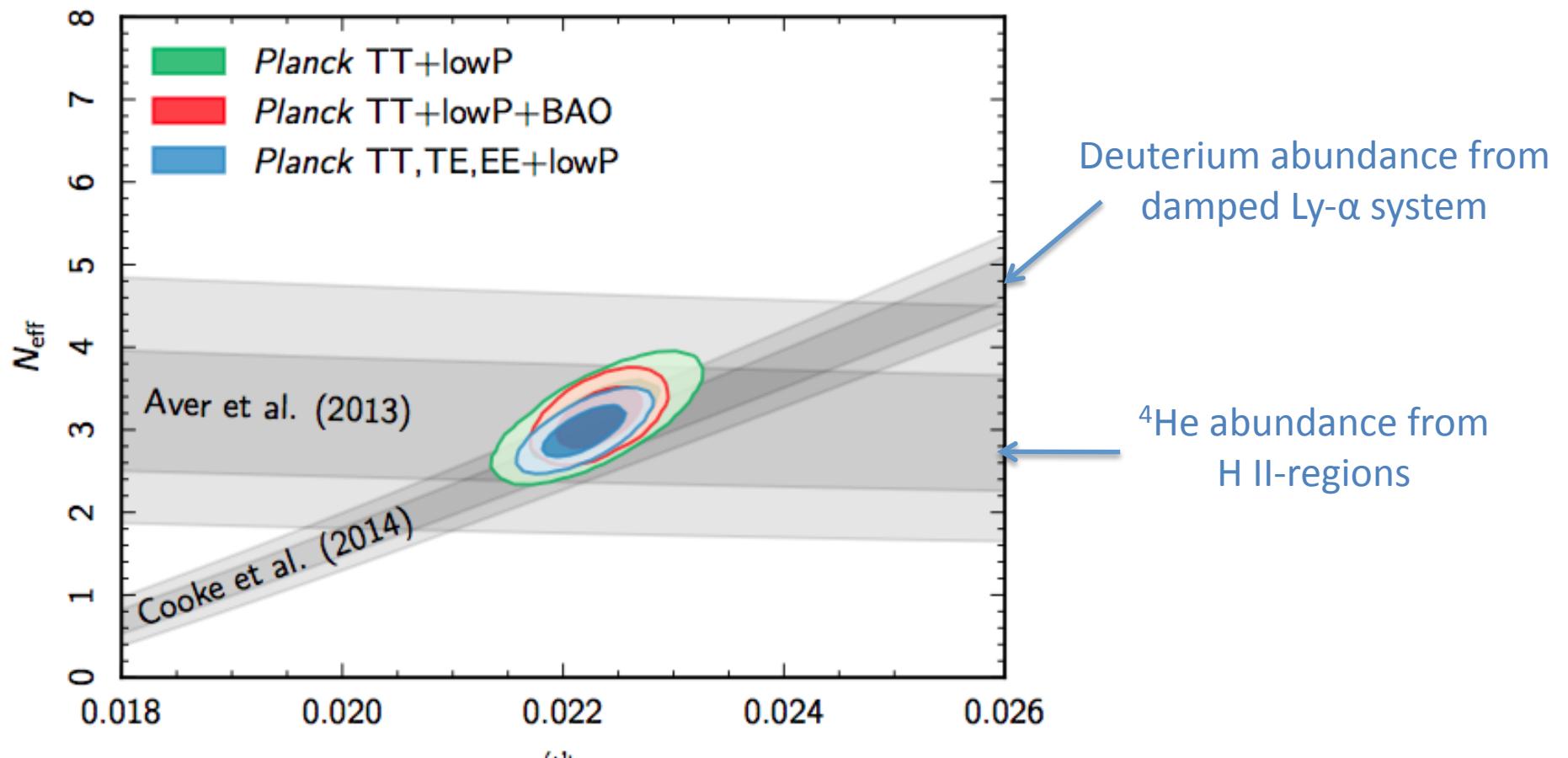


Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
N_{eff}	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$

Data confirm standard model expectation
(CMB only, no more hints of additional light particles)

[*Planck* collaboration 2015]

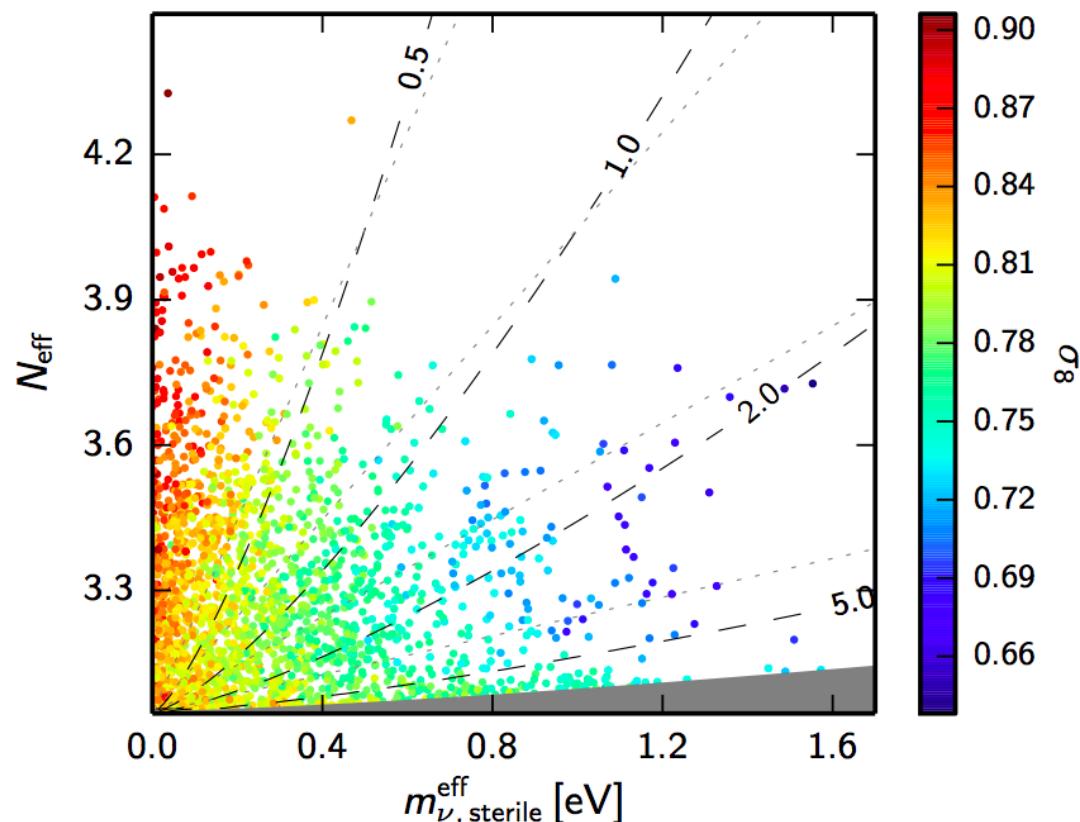
Planck results vs. BBN



Excellent match with BBN expectation + astrophysical element
abundance measurements

[*Planck* collaboration 2015]

Planck constraints on eV-mass sterile neutrinos



Planck data not compatible with a fully thermalised eV-mass neutrino

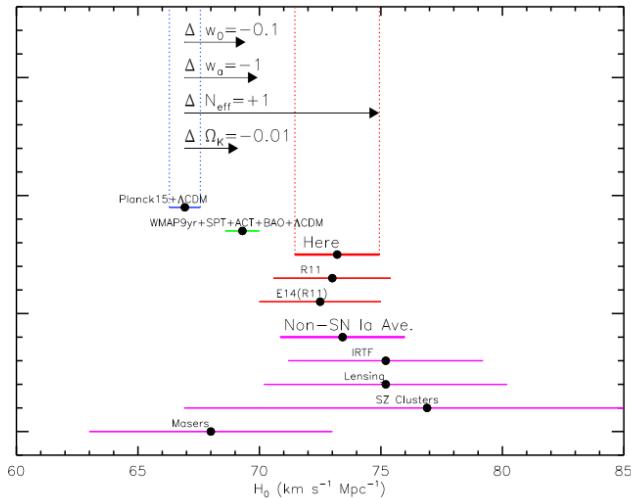
Want to save the scenario?

Need to suppress production of steriles (e.g., lepton asymmetry, new interactions, etc.)

$$\left. \begin{array}{l} N_{\text{eff}} < 3.7 \\ m_{\nu, \text{sterile}}^{\text{eff}} < 0.38 \text{ eV} \end{array} \right\} 95\%, \textit{Planck TT+lowP+lensing+BAO.}$$

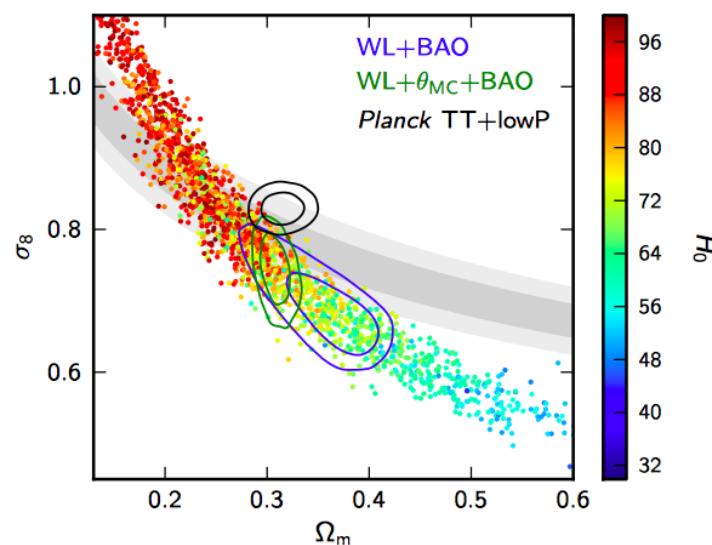
[*Planck* collaboration 2015]

Discrepancies with other observations



Hubble parameter
too low?

Local measurement of H_0 [Riess+ 2016]



Too much power at small
scales?

Galaxy weak lensing [CFHTLens 2012, 2013]
Cluster counts [Planck collaboration 2015]

Discrepancies with other observations

underestimated uncertainties/systematics

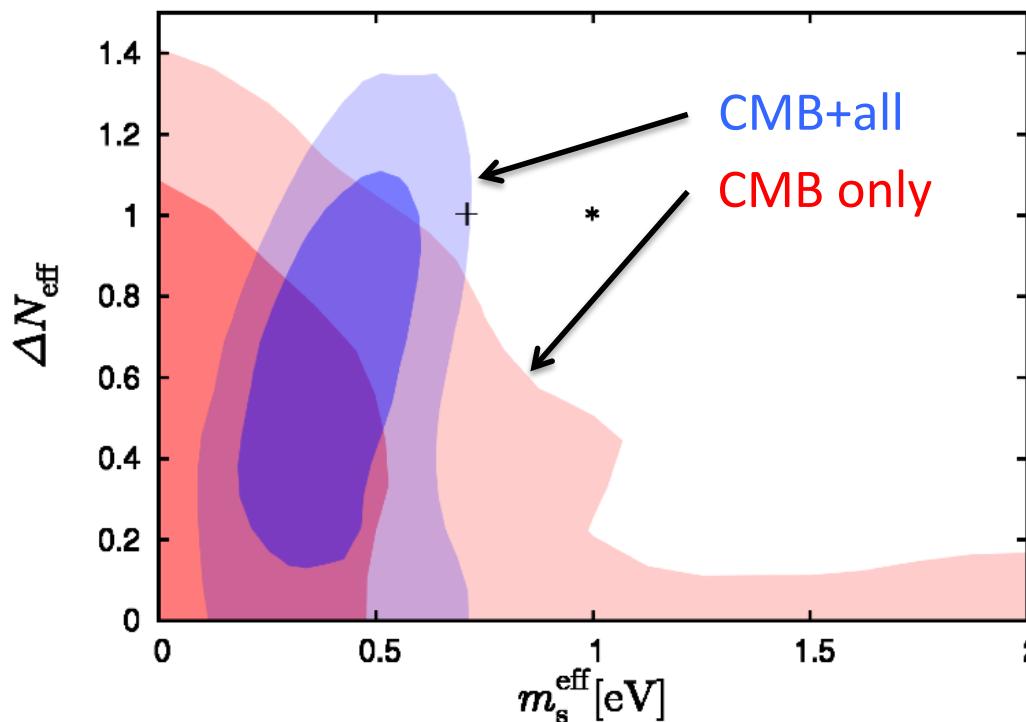
or

sign of new physics beyond base Λ CDM

?

Sterile neutrinos after all?

- Extra radiation increases inferred H_0
- Neutrino mass suppresses inferred σ_8



$\Delta\chi^2 \approx 13$
with respect to
 ΛCDM

[JH & Hasenkamp 2013; Battye+ 2013, Wyman+ 2013]

Sterile neutrinos after all?

- No trace in CMB data alone
- SN, BAO and galaxy clustering data do not support this scenario either
(cf. BOSS DR12) [Alam+ 2016]
- Evidence entirely driven by H_0 and cluster data
- Neutrino mass and N_{eff} both lead to larger ω_m , decreasing quality of fit to CMB, BAO [Leistedt+ 2014]

Not entirely convincing...

Conclusions

- The Universe continues to be boring: no evidence for anything unexpected in the cosmological neutrino sector
- Final *Planck* data release soon (includes large scale HFI polarisation data)
- Future data (CMB lensing, LSS surveys) in combination with *Planck* will greatly increase sensitivity to neutrino parameters